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LARP

Integrated quench protection model for Nb_3Sn high-field accelerator magnets

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Context I

- Nb_3Sn:
  - For field strengths 10 - 18 T
  - Brittle & strain sensitive material
    - “Wind & react”
      - Nb_3Sn structure formation at ~ 650° C (for days)
    - Impregnated coils
- LBNL: Development of high-field Nb_3Sn dipoles and quadrupoles
- U.S. LARP collaboration (LBNL, FNAL, BNL, SLAC): Demonstration of Nb_3Sn technology matureness for the high luminosity LHC
  - Large aperture quadrupoles for the interaction region upgrade
- Quench protection is one of the several challenges in the development of long Nb_3Sn accelerator magnets

Outline

Introduction

- Quench process and protection challenges in long Nb_3Sn magnets
- Technology jump from LHC NbTi
- State-of-the-art quench protection & its limitations
- Research in my PhD

Qcode development

- Modeling goals
- Status and demonstration

Summary

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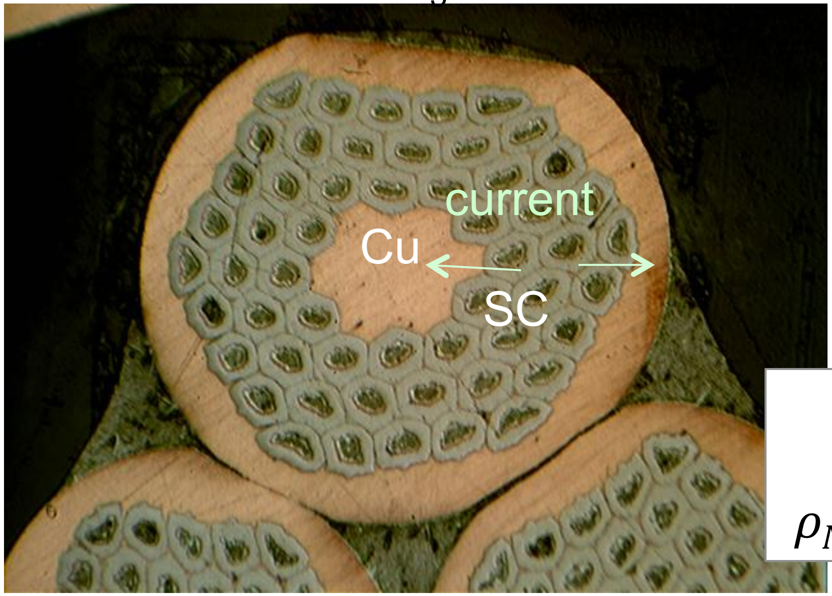
Summary

Quench – A local resistive transition + thermal runaway

Strands in Nb$_3$Sn cable



$$@\ 20\ K\ and\ 10\ T:$$
$$\rho_{Cu} \approx 5 \cdot 10^{-10}\,\Omega m$$
$$\rho_{Nb_3Sn} \approx 2.6 \cdot 10^{-7}\,\Omega m$$

Joule heating: $Power/Volume = \rho_{Cu} J_{Cu}^2$

Example

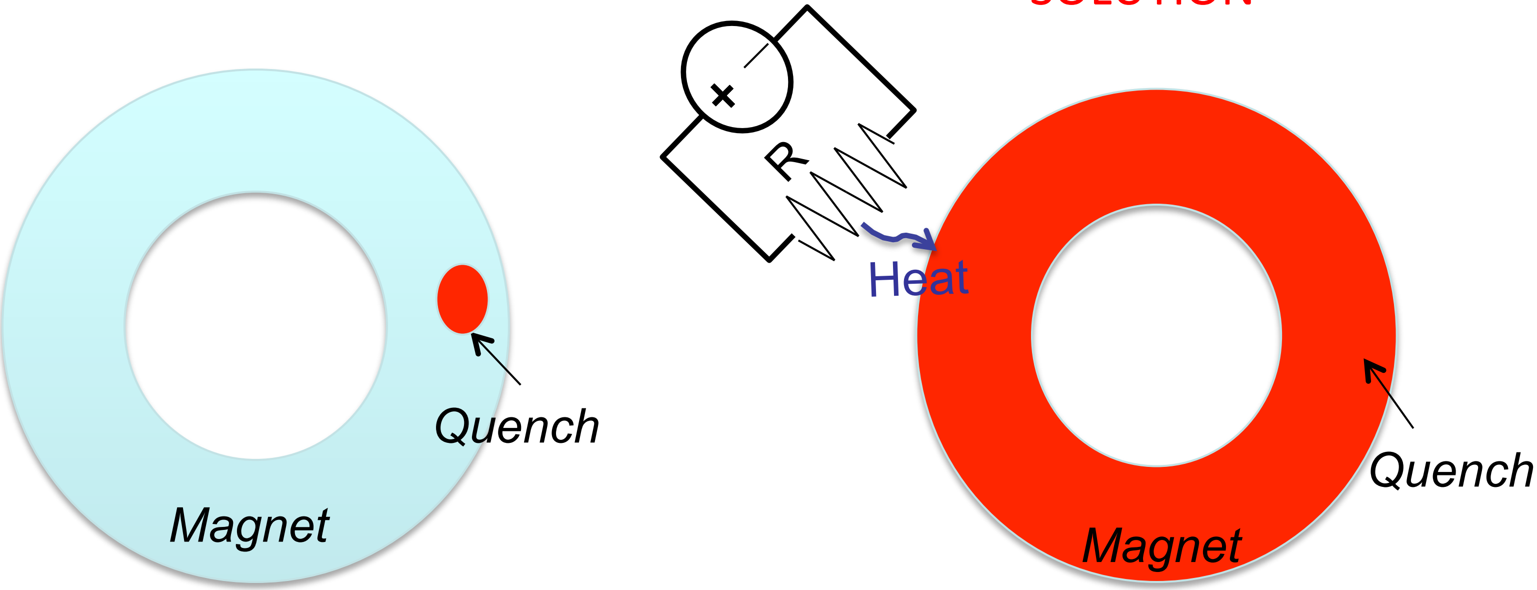
Nb$_3$Sn LARP HQ: $J_{Cu} \approx 2000 \dfrac{A}{mm^2}$ $(Quench\ @\ I_{ss} @\ 1.9\ K\ and\ 15\ T)$

$\rightarrow Power/Volume \approx 2\ GW/m^3$

Higher the copper current density, faster the action needed.

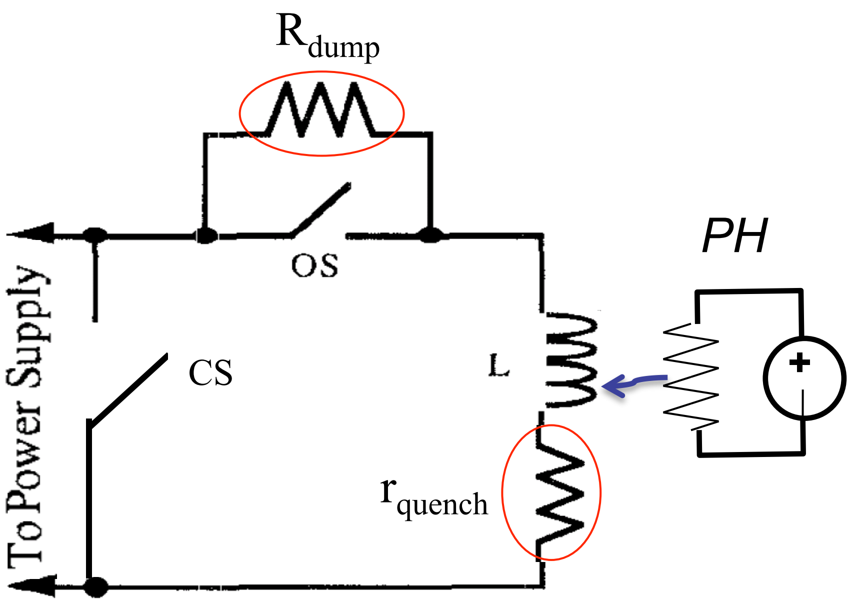
The stored magnetic energy dissipated in the resistive heating

Temperature rise: $\Delta T = \frac{\Delta E}{V \cdot C_V(T)}$

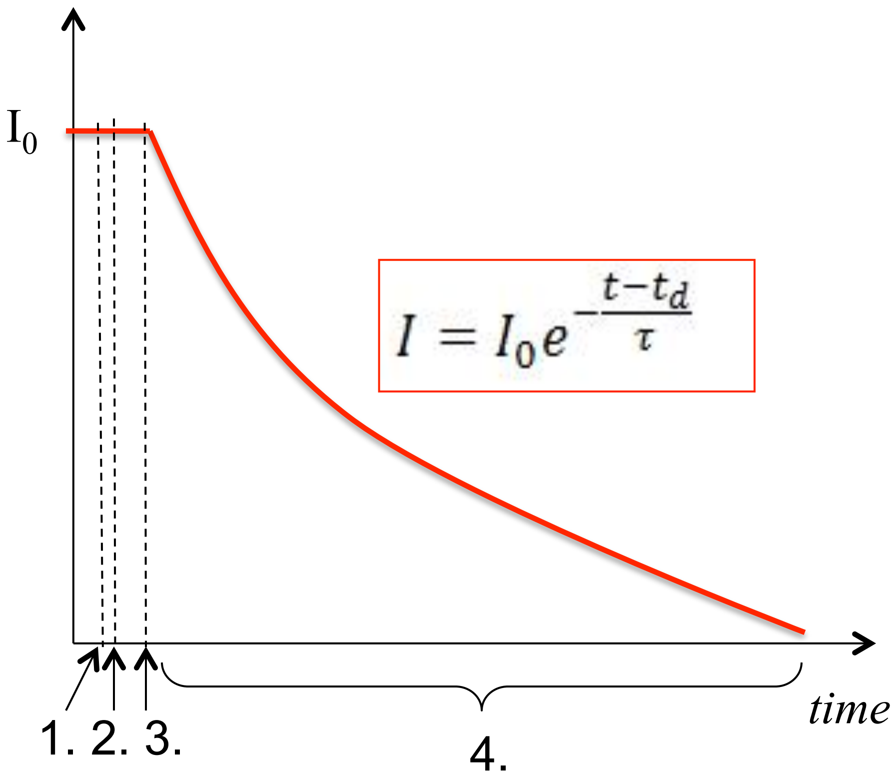


Larger the stored energy, the larger the resistive volume needed to absorb it.

Basic quench protection circuit



$\tau = L/(R_{dump} + r_{quench})$



$$I = I_0 e^{-\frac{t-t_d}{\tau}}$$

1. Quench detection

2 .Current supply disconnection, activate PH and R_{dump}

3. Protection heater efficient + R_{dump} connected

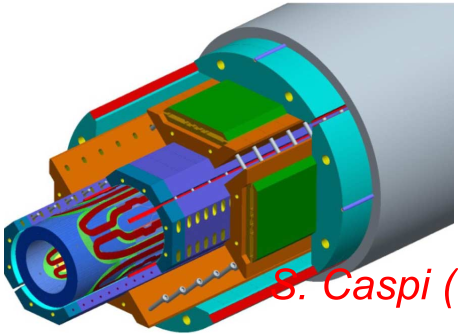
→ 4. Circuit resistance increase → Current decay

LARP R&D Nb$_3$Sn vs. LHC NbTi

Long Quadrupole (LQ)

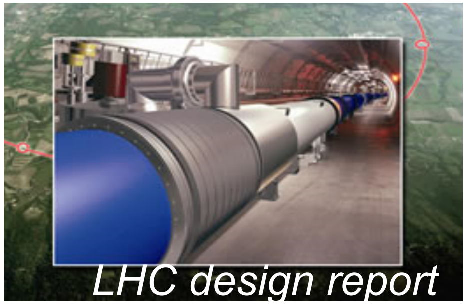
G. Ambrosio (2011)

High-gradient Quad. (HQ)



S. Caspi (2011)

LHC NbTi Main Dipole (MB) and IR quad. (MQXA/B)



LHC design report

Parameters at 1.9 K	LQ	HQ	MB	MQXA	MQXB
Length (m)	3.6	0.9	14.3	6.4	5.5
Aperture (mm)	90	120	56	70	70
Short sample current I_{ss} **(kA)	15	19	11.8	~7.5	~11.8
Copper current density, J_{Cu} (A/mm^2)	1600	2000	930	~930	~1200
Magnetic field at Iss (T)	13	14.8	8.6	8.6	7.7
Gradient at Iss (T/m)	240	214	N/A	215	215
Stored energy at I_{ss} (kJ/m)	560	1400	480	360	0.25
Self inductance at I_{ss} (mH/m)	5	~7.7	7	14	3.5

** In LHC parameters for nominal operation

Next LARP goal: Long HQ (LHQ) – **3.6 m scale up of HQ**

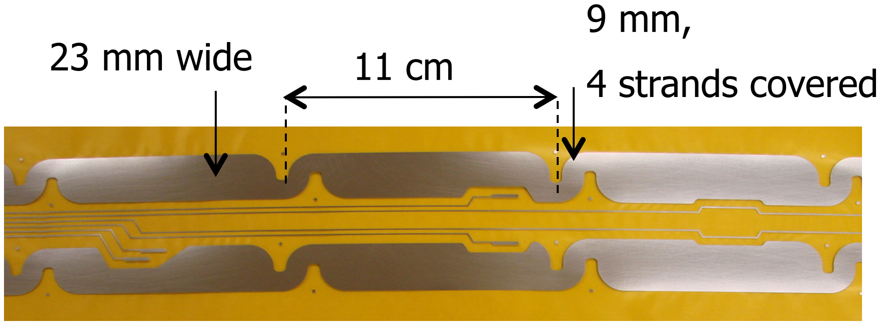
Full-scale IR quad: **6 – 10 m** long "HQ"

State-of-the-art quench protection and its limitations

- LARP Trace technology: 25 µm stainless steel circuits on a 45 µm Kapton® sheet
- Dump resistor in magnet tests

HQ – 1 m

LQ – 3.6 m



H. Felice (2009)

Limitations:

1) Long magnets → Heater powering
2) Superfluid He → "Bubbles" in inner layer heaters
3) Reaction temperatures & Kapton → No heaters between layers

Can this technology be suitable for longer magnets?

Research in my PhD

GOAL:

Protect long high-field Nb_3Sn magnets.

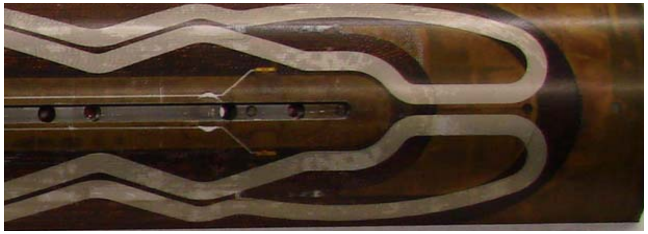
Find a technical solution to quench the winding fast and uniformly after a quench.

Research questions:

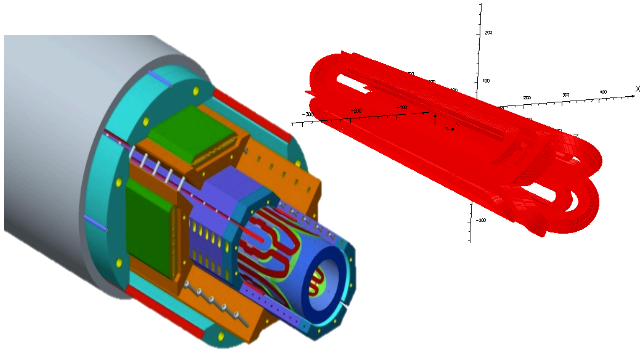
1) What is an optimum protection heater layout for any given magnet?
   - **"Given magnet"**: length, stored energy, cable, operation, "environment"
   - **To be minimized**: Temperature peaks and gradients, voltages
   - **Variables**: Protection heater layout, materials, powering, external circuit
2) Is there a length / stored energy limitation in protecting magnets using protection heaters?
3) Distribution of resistive and inductive voltages during a quench

Context II

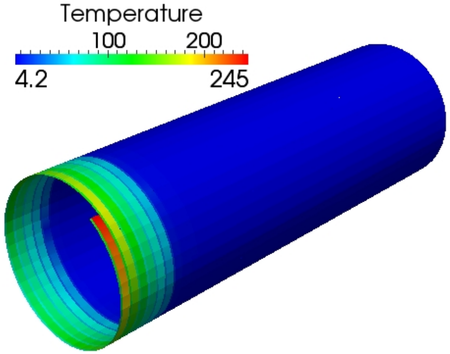
Starting point:



Protection of short R&D quadrupoles and dipoles
H. Felice (2009)



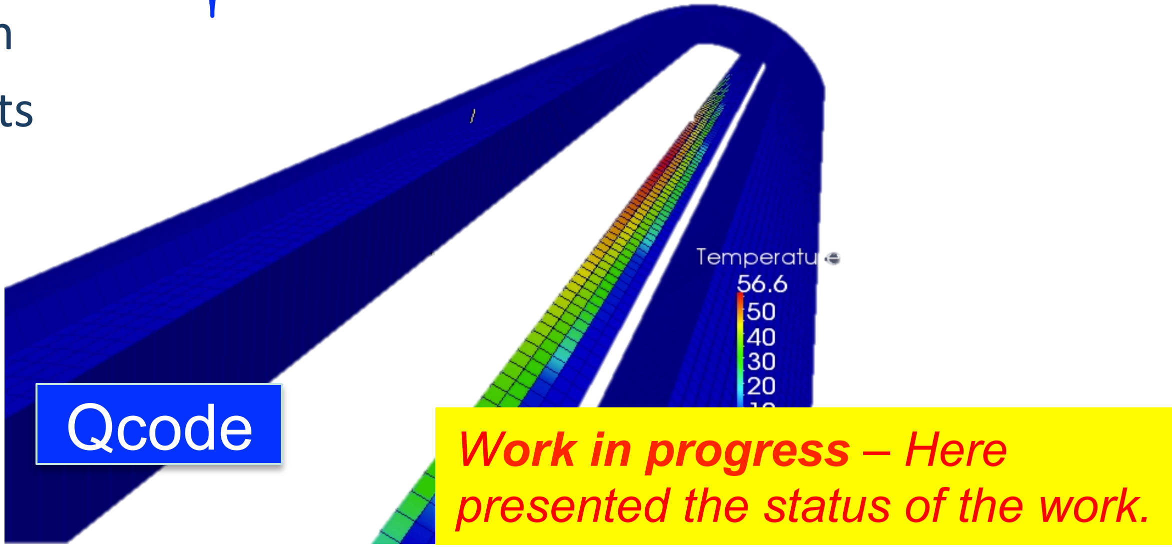
Integrated magnet design at LBNL
S. Caspi (2006)



Quench propagation calculation
D. Arbelaez (2010)

In my PhD: Systematic protection heaters study in different magnets

- Integrate a numerical quench protection simulation model with other analysis software
- Protection experiments



Qcode

Work in progress – Here presented the status of the work.

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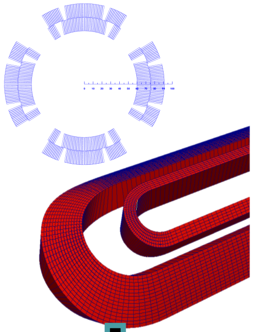
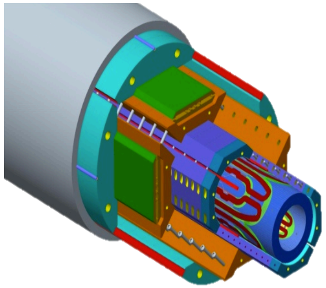
Integrated *3-D* magnet design at LBNL

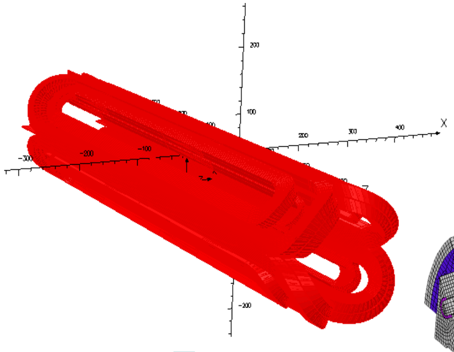
2D cross-section from ROXIE or PKLBL +

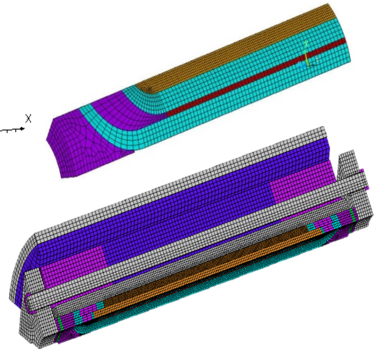
NEW ADDITION!

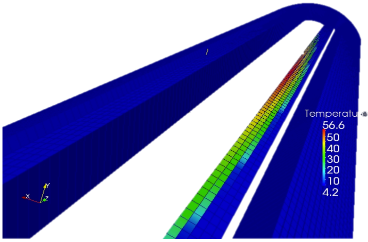
BEND | **CAD** | **VF Opera 3D** | **ANSYS 3D** | **Qcode**











Turn by turn coil model for cos nθ magnets

End parts and island fabrication

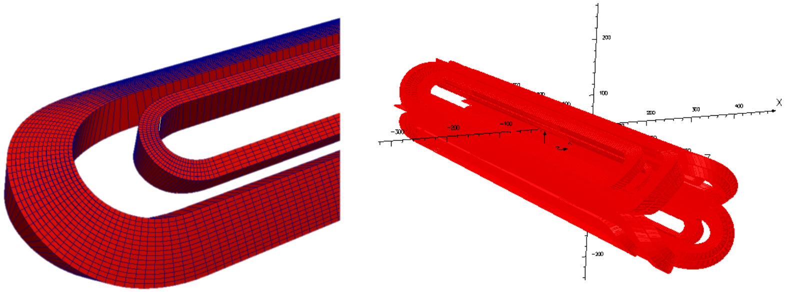
End optimization and peak field management (length of yoke)

3D Mechanical Analysis

Thermal & electrical quench analysis

S. Caspi, and P. Ferracin, "Towards Integrated Design and Modeling of High Field Accelerator Magnets" (2006)

Qcode idea



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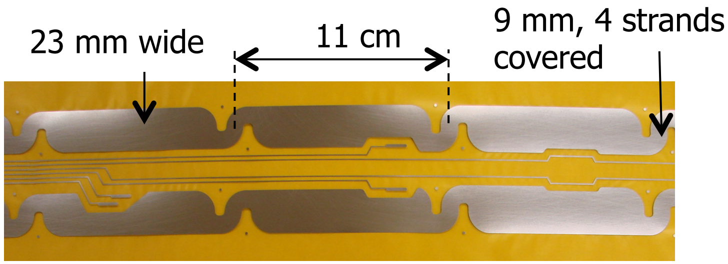
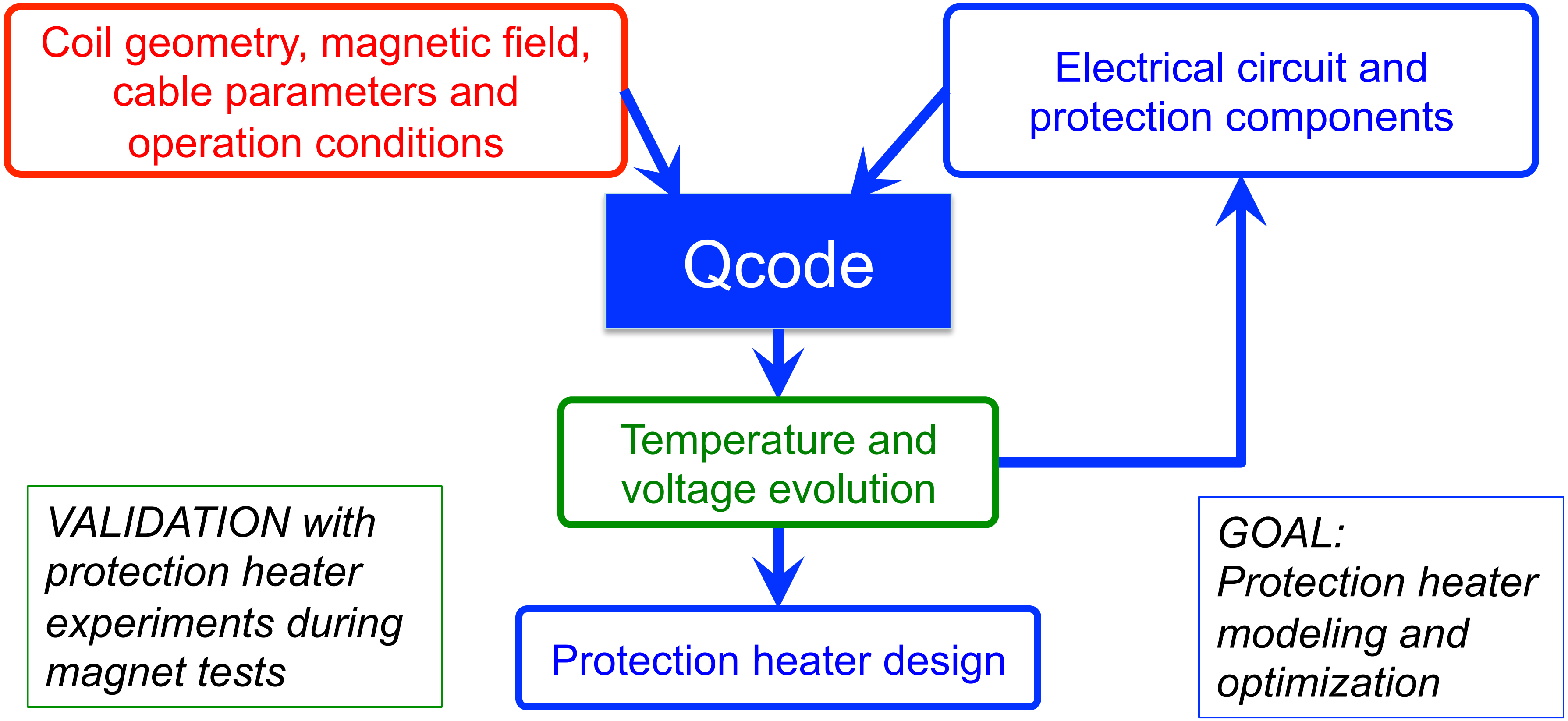


Example of a heater design (LARP LQ)



Coil geometry, magnetic field, cable parameters and operation conditions

Electrical circuit and protection components

Qcode

Temperature and voltage evolution

Protection heater design

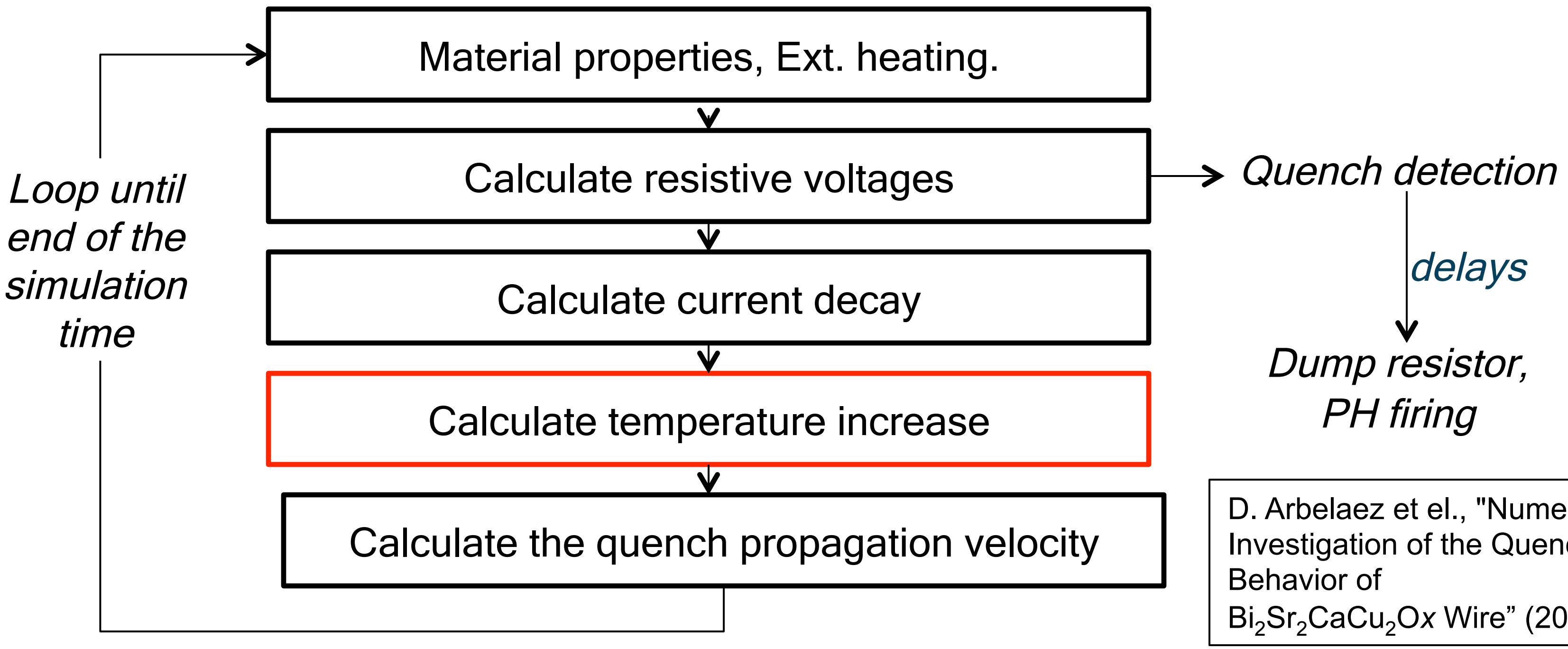
VALIDATION with protection heater experiments during magnet tests

GOAL: Protection heater modeling and optimization

Programming starting point

- A code by D. Arbelaez (LBNL): Quench propagation in a wire
  - Longitudinal segmentation
  - Material properties in each cross-section
  - Computation of heat fluxes in / out (finite difference method) + internal heating
- *Developments:* Cable and coil, magnetic field, protection heaters, flexibility

Calculation loop



Material properties, Ext. heating.

Calculate resistive voltages

Calculate current decay

Calculate temperature increase

Calculate the quench propagation velocity

Loop until end of the simulation time

Quench detection

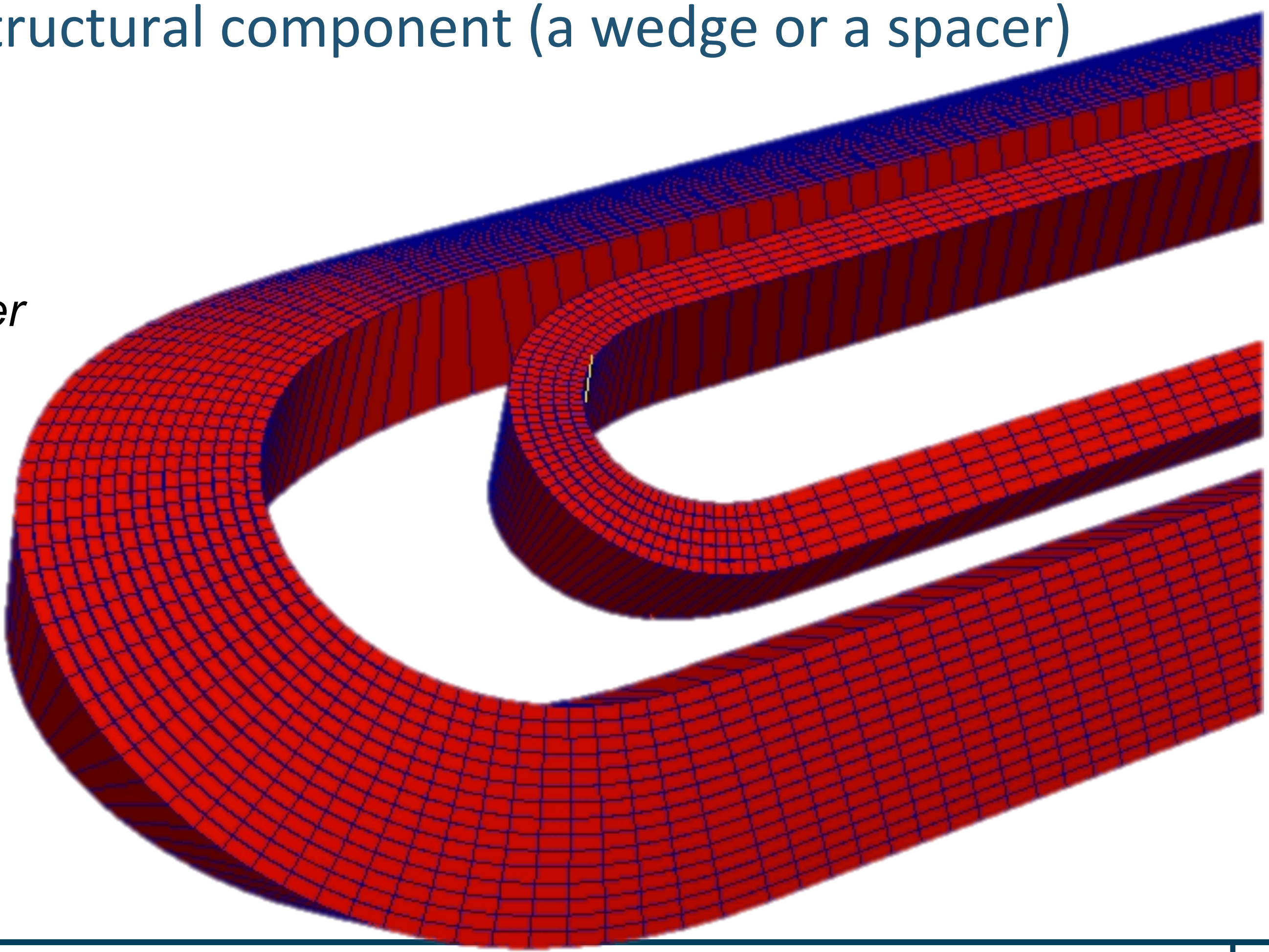
delays

Dump resistor, PH firing

D. Arbelaez et el., "Numerical Investigation of the Quench Behavior of $Bi_2Sr_2CaCu_2Ox$ Wire" (2010)

Coil geometry

- Input: Coil geometry file
- Cable discretization
- Lateral thermal neighbors
    - Detection of a structural component (a wedge or a spacer)



Example geometry: Inner layer of the HQ coil by courtecy of S. Caspi

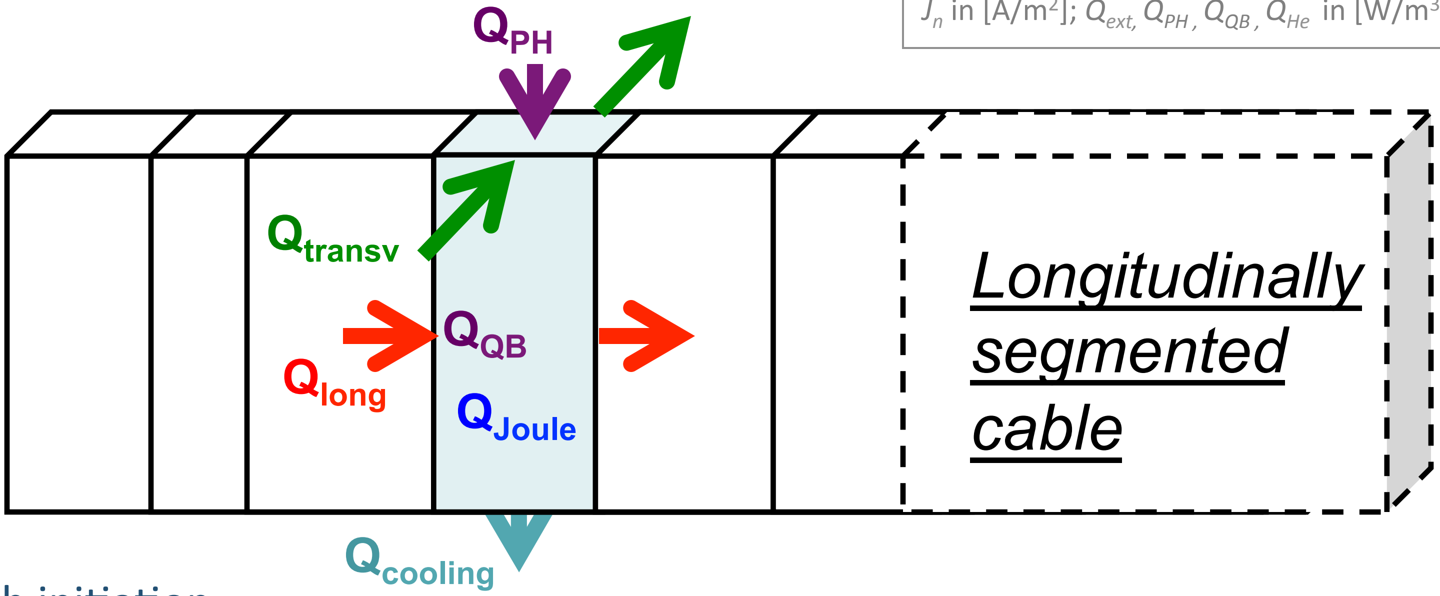
The heat transfer model

$$\gamma C_p(T)\frac{\partial T}{\partial t} = Q_{long} + Q_{transv} + Q_{layer} + Q_{Joule} + Q_{PH} + Q_{QB} + Q_{ext} - Q_{He}$$

$$= \frac{\partial}{\partial x}\left(\kappa_x(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa_y(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\kappa_z(T)\frac{\partial T}{\partial z}\right) + \rho(T,B)J_n^2$$

$$+Q_{PH} + Q_{QB} + Q_{ext} - Q_{He}$$

x, y, z in [m]; *t* in [s]; *T(x,y,z,t)* in [K]; $C_p(T)$ in [J/(K-kg)];
γ in [kg/m^3]; *κ(T)* in [W/(K-m)]; *ρ(T,B)* in [Ω-m];
J_n in [A/m^2]; Q_{ext}, Q_{PH}, Q_{QB}, Q_{He} in [W/m^3]

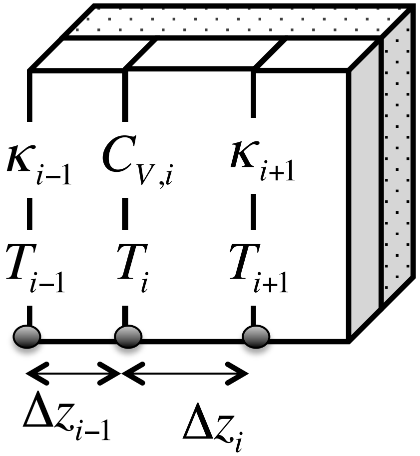


- Quench initiation
- In each segment balanced the heat fluxes in / out (*n* x 1D)
- Finite difference with 6th order Runge-Kutta algorithm & adaptive time-stepping
- **Temperature rise → Current sharing → *Quench***

Temperature gradients numerically

For the longitudinal and transversal heat flux computation.

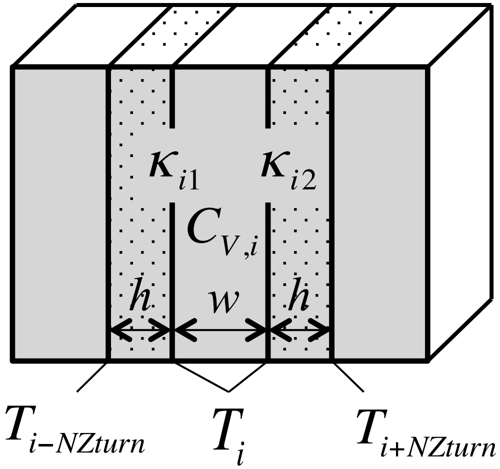
Longitudinal



$$\frac{\partial}{\partial z}\left(\kappa_z(T)\frac{\partial T}{\partial z}\right)$$

$$= \frac{1}{(\Delta z_{i-1}+\Delta z_i)^2}\left[\kappa_{i-1}\left[\left(2+\frac{\Delta z_i}{\Delta z_{i-1}}\right)T_{i-1} - \left(2+\frac{\Delta z_{i-1}}{\Delta z_i}+\frac{\Delta z_i}{\Delta z_{i-1}}\right)T_i + \frac{\Delta z_{i-1}}{\Delta z_i}T_{i+1}\right] + \kappa_{i+1}\left[\frac{\Delta z_i}{\Delta z_{i-1}}T_{i-1} - \left(2+\frac{\Delta z_{i-1}}{\Delta z_i}+\frac{\Delta z_i}{\Delta z_{i-1}}\right)T_i + \left(2+\frac{\Delta z_{i-1}}{\Delta z_i}\right)T_{i+1}\right]\right]$$

Transversal

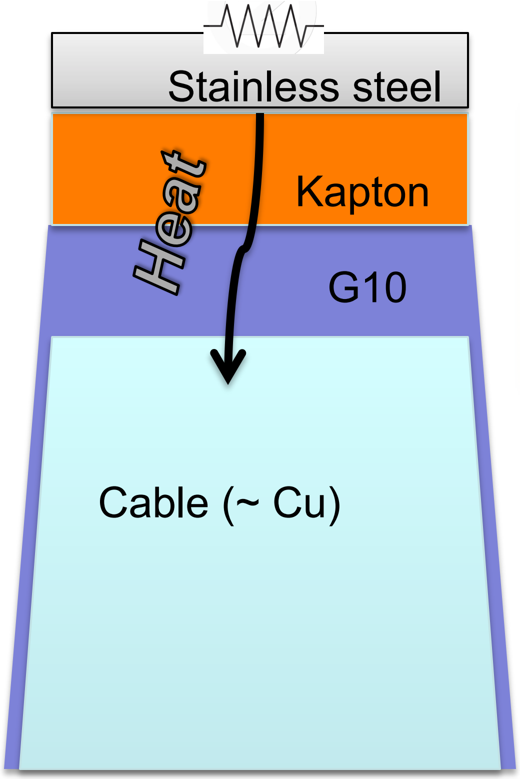


$$\frac{\partial}{\partial x}\left(\kappa_x(T)\frac{\partial T}{\partial x}\right)$$

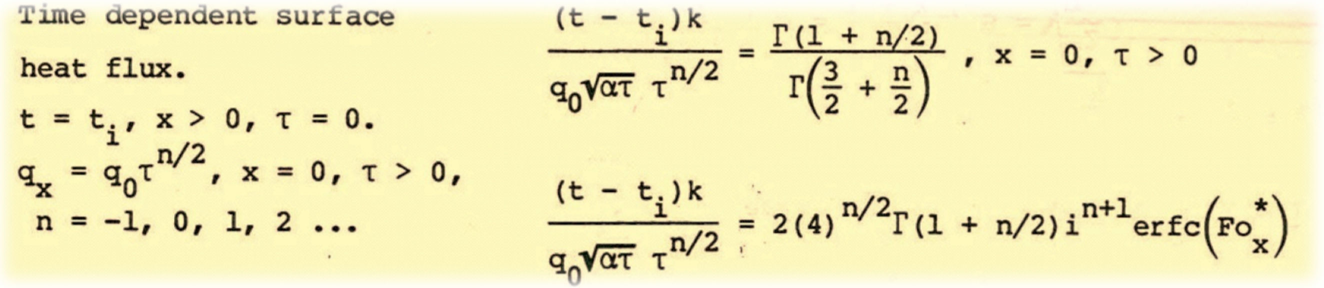
$$= \frac{1}{w_{cable}h_{ins}}\left[\kappa_{i1}\left(T_{i-Nz_{turn}} - T_i\right) + \kappa_{i2}\left(T_{i+Nz_{turn}} - T_i\right)\right]$$

Heat flux from protection heaters

- Time and space dependency
- Analytical solution under study
- Validation with experiments and FEM



Analytical approximations exists but are not straight forward with non-linear material properties


Time dependent surface heat flux.

$t = t_i,\ x > 0,\ \tau = 0.$

$q_x = q_0\tau^{n/2},\ x = 0,\ \tau > 0,$

$n = -1, 0, 1, 2 \ldots$

$$\frac{(t - t_i)k}{q_0\sqrt{\alpha\tau}\ \tau^{n/2}} = \frac{\Gamma(1 + n/2)}{\Gamma\left(\frac{3}{2} + \frac{n}{2}\right)},\ x = 0,\ \tau > 0$$

$$\frac{(t - t_i)k}{q_0\sqrt{\alpha\tau}\ \tau^{n/2}} = 2(4)^{n/2}\Gamma(1 + n/2)\,i^{n+1}\mathrm{erfc}\left(Fo_x^*\right)$$

Analytical formula can be coded into the program if an acceptable match with FEM and experiment

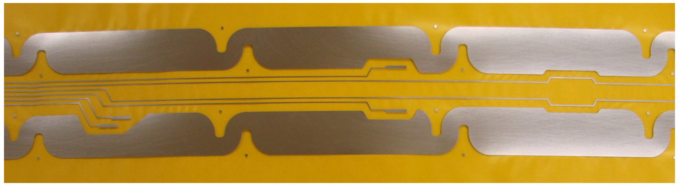
Heater layout

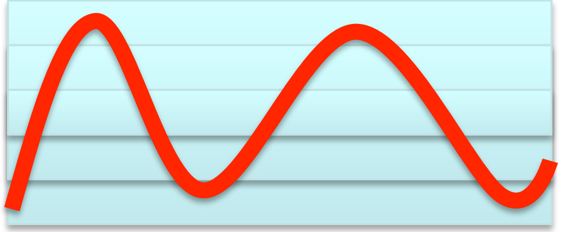
Goal is to model any heater geometry:

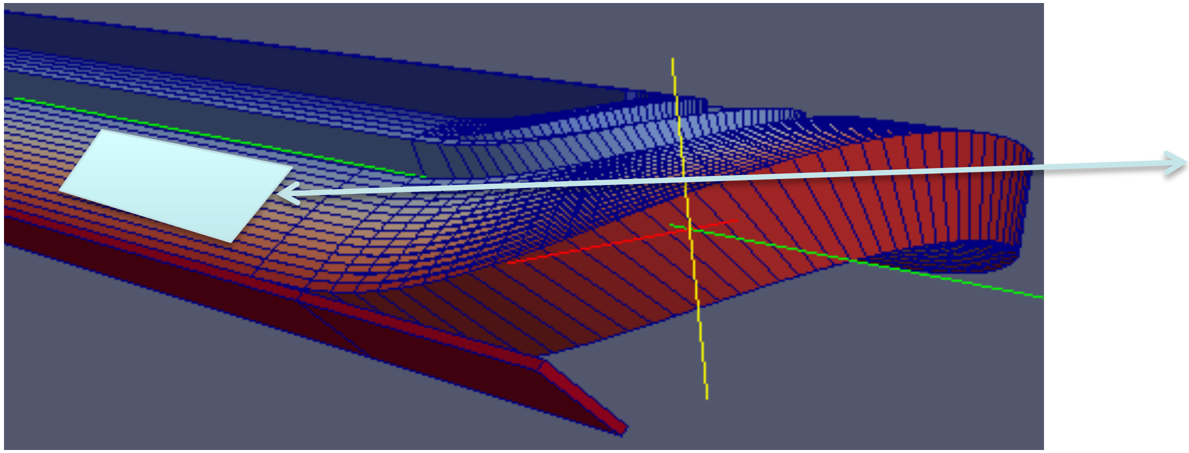
1) Continuous
2) Heating stations
3) Combination

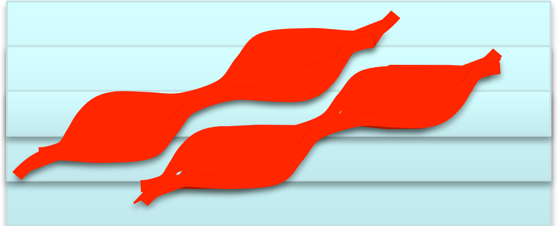
Optimization: Width, period, “amplitude”, …

Examples









Model status and demonstration 1

Development status:

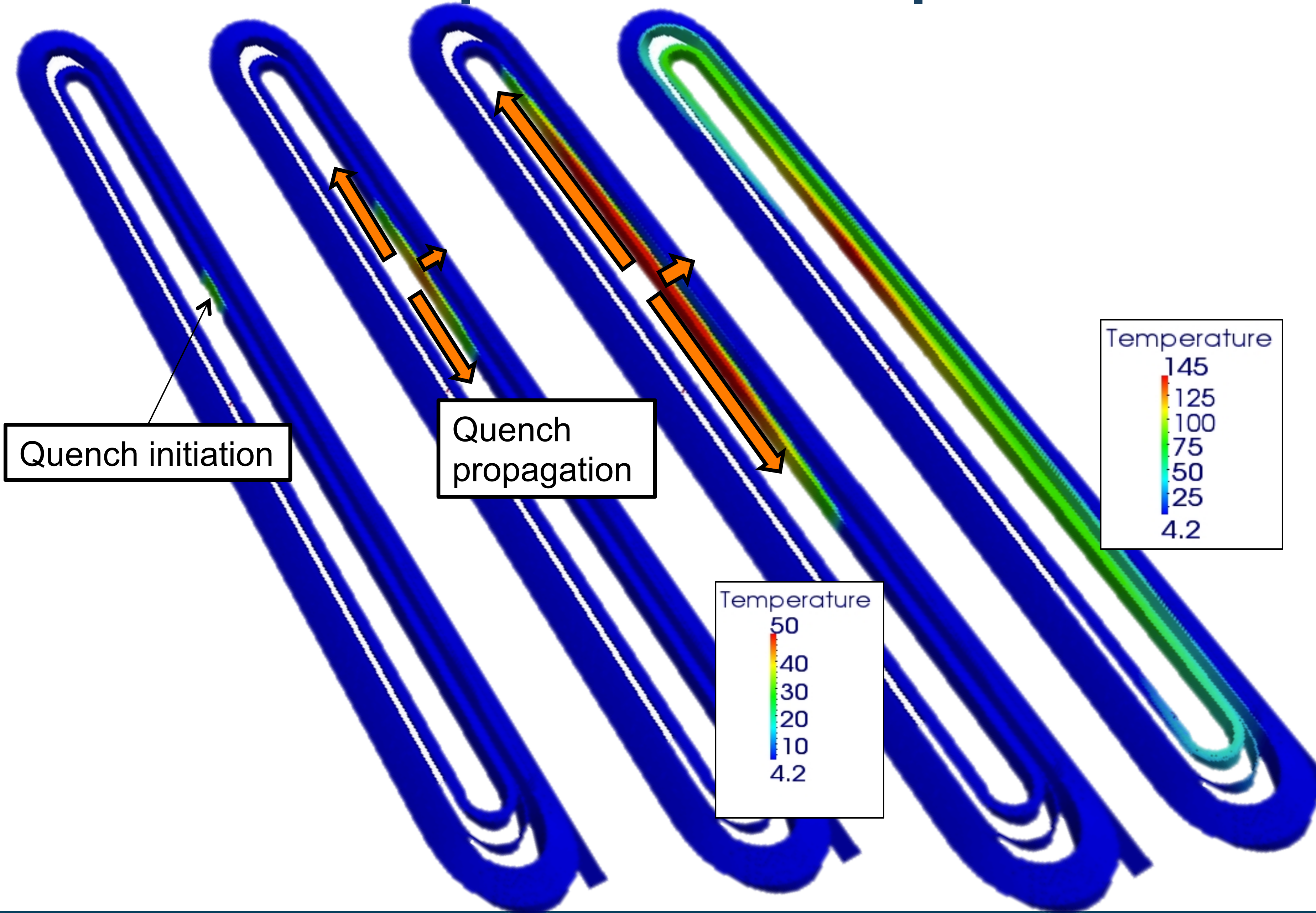
- Testing of propagation velocities and hotspot temperatures in progress
- Magnetic field is initially constant and scaled down with current
- Protection heater layout “by hand”
- Heat from protection heaters directly into the strands

Example 1 – Quench propagation

Parameters:

- Initial current, field and inductance: 14 800 A, 11.7 T, 6 mH
- Dump resistor: 30 mΩ, trigger delay: 10 ms, detection threshold: 125 mV
- No protection heaters

Temperature development



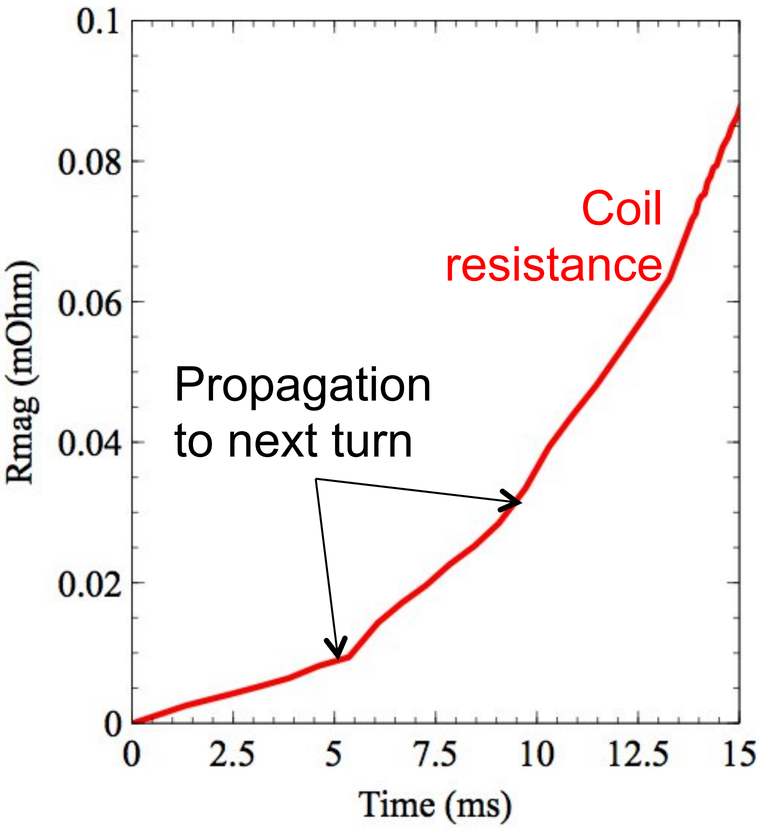
Quench initiation

Quench propagation

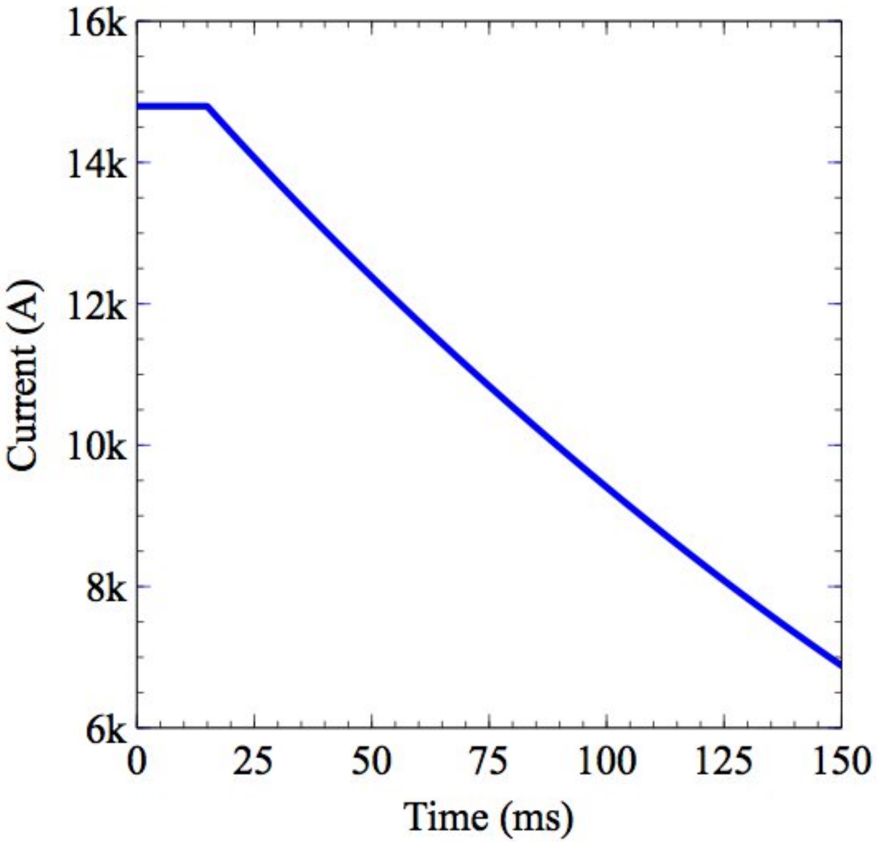
Example output

Type of output that can be compared with magnet tests

"Quench propagation"

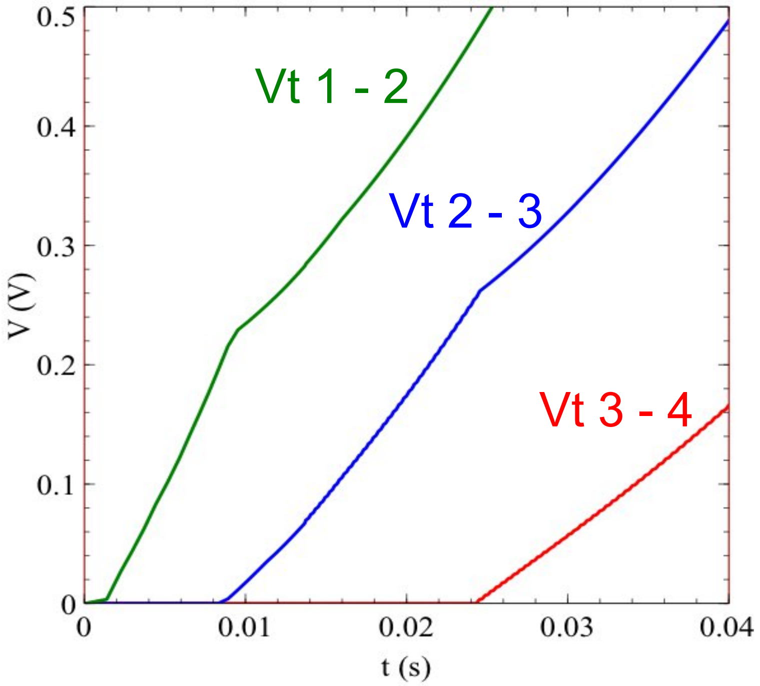


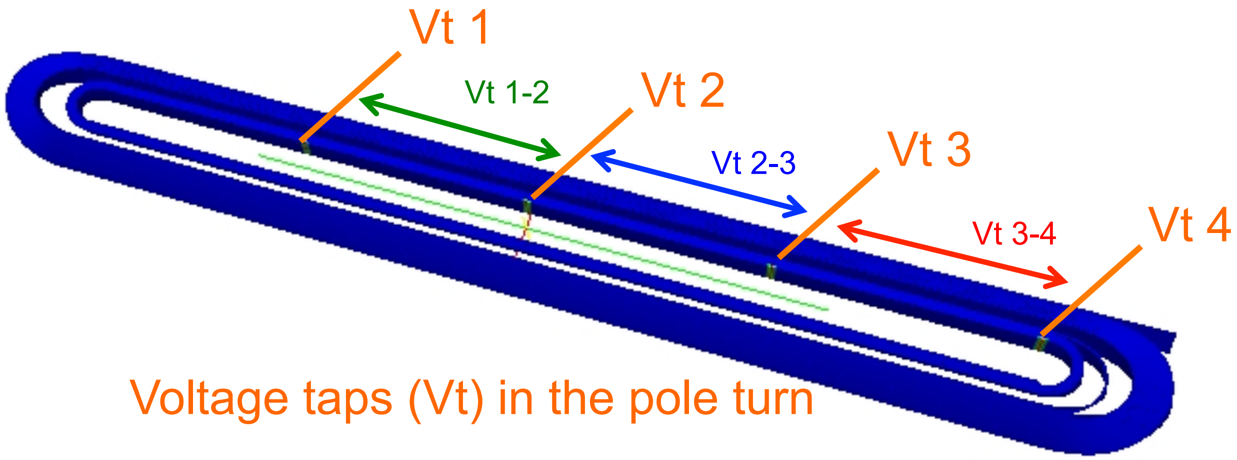
Current decay



Voltage taps

- Resistive voltage across each segment → Voltage tap simulation in arbitrary locations
- Calculation of inductive voltages will be implemented, then:
  - Turn-to-turn and coil to PH voltages
  - Voltage tap signals vs. quench type in a magnet test





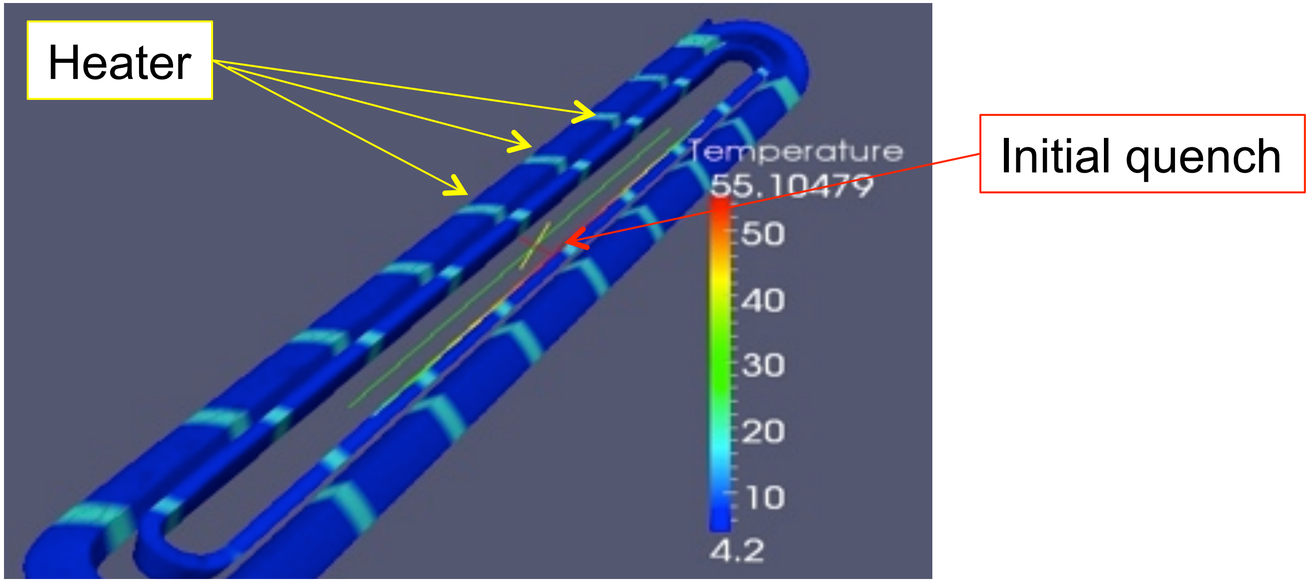
Voltage taps (Vt) in the pole turn

Model status and demonstration 2

Example 2 – Protection heaters

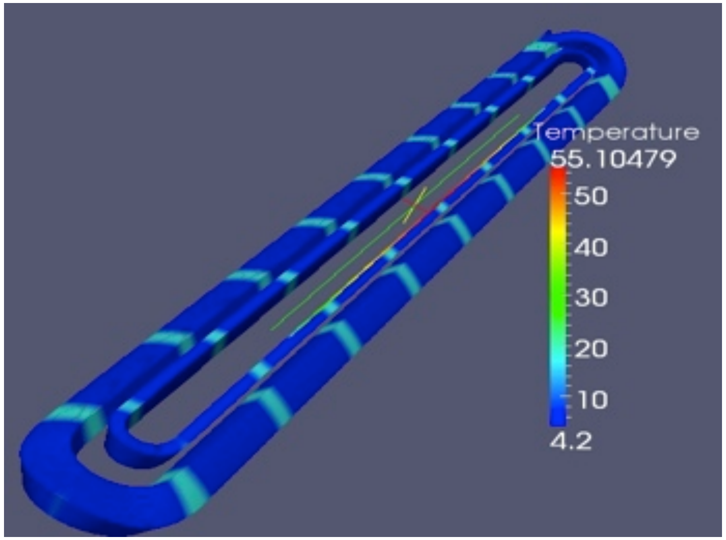
Parameters:

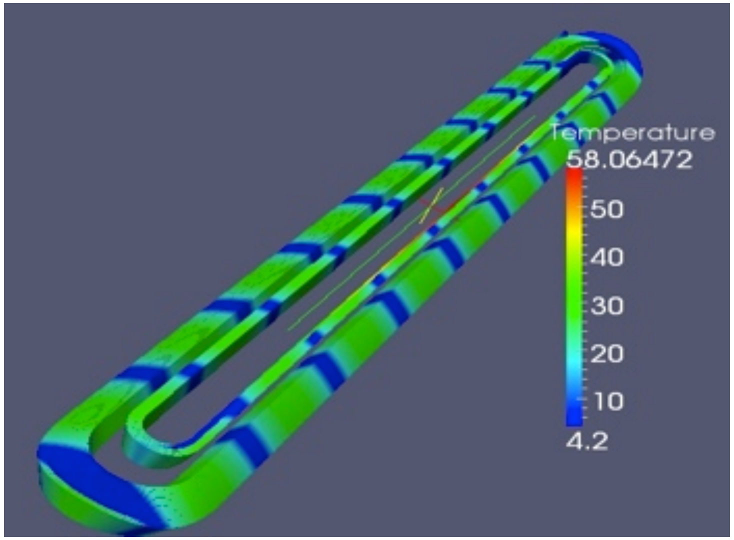
- Initial current, field and inductance: 14 800 A, 11.7 T, 6 mH
- Protection heaters fired 5 ms after the detection
  - Heating stations every ~ 20 cm, covering ~ 4 cm
- No dump resistor
- No turn-to-turn propagation

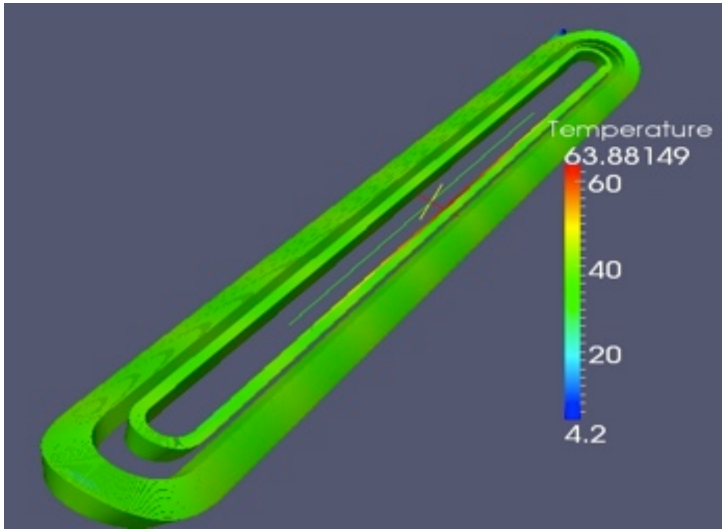


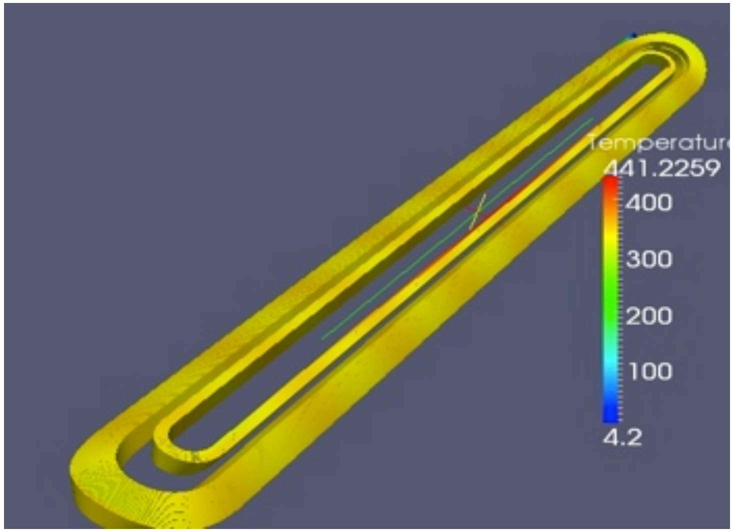
Protection heaters example

Example: Protection heaters cover ~ 4 cm periodically every ~ 20 cm.









Animation

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Modeling

- Modeling goals
- Development status

Summary

Summary

- Large coverage of efficient protection heaters needed for protecting high-field Nb_3Sn accelerator magnets in case of a quench
- To define general guidelines for heater geometries and protection design in different magnets , an integrated tool for protection design, *Qcode*, is being developed at LBNL
- Qcode modeling goals:
  - Multi-physics of quench propagation, temperature and voltage development
  - Protection heater geometry and heat diffusion in the coil
  - Fast & flexible: Coil geometry and magnetic field map from external sources
  - Realistic & reliable: Validation against other software and experiments in R&D magnets
  - Optimization algorithms for the heater design
  - Possible extension: Simulation in “inverse mode” to relate voltages tap signals during a magnet test to a quench type and origin
- Qcode development status:
  - Quench propagation in a coil and protection heaters using simplifications
  - Programming work in progress and first benchmarking of the model expected at the beginning of 2012

Thank you!

Related work and references

LARP magnet R&D:

G. Ambrosio et al., “Test Results of the First 3.7 m Long Nb3Sn Quadrupole by LARP and Future Plans”, IEEE Trans. On Applied Superconductivity, Volume 21(3), page 1858, June 2011

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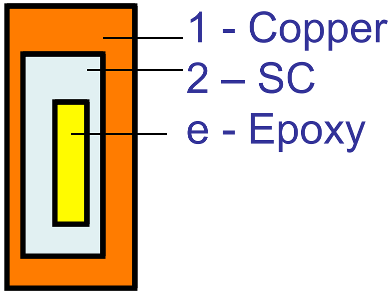
About material properties

Homogenized volumetric heat capacity:

$$\gamma C_p = \upsilon_1 \gamma_1 C_{p,1} + \upsilon_2 \gamma_2 C_{p,2} + \upsilon_e \gamma_e C_{p,e}$$

Insulation around cable not accounted



$$\upsilon_1 + \upsilon_2 + \upsilon_e = 1$$

Thermal conductivity:

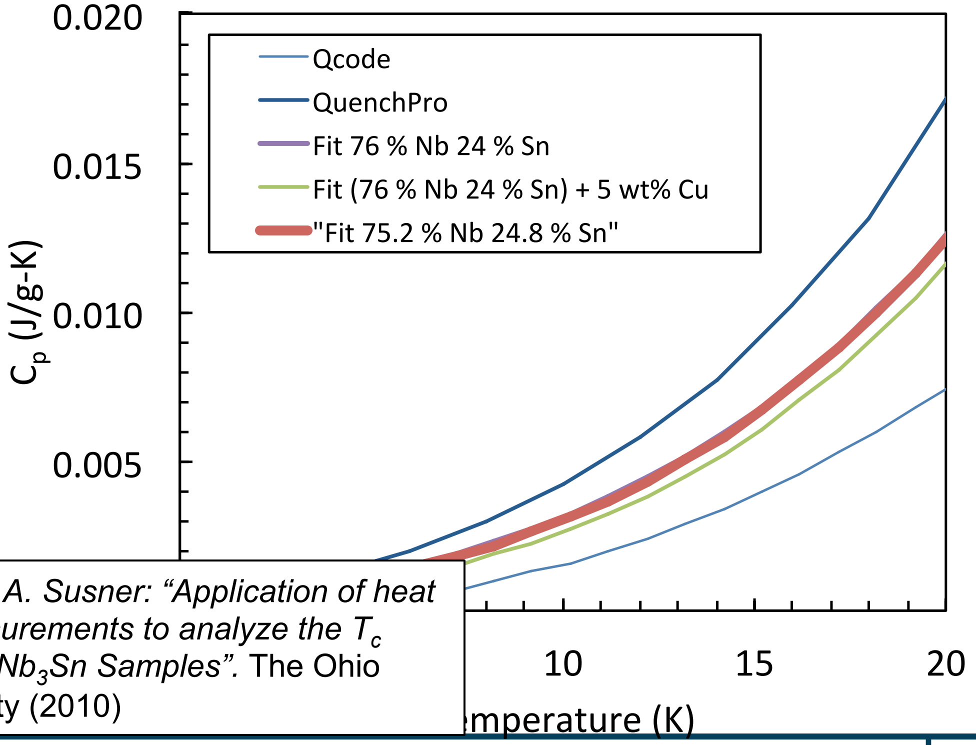
$$\kappa = \nu_1 \kappa_1 (1 - \nu_e)$$

Electrical resistivity:

$$\rho = \frac{\rho_1 \rho_2}{\nu_1 \rho_2 + \nu_2 \rho_1}$$

Joule heat generated:

$$\rho(T,B) J_n^2 \times (1 - \upsilon_e)$$



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